An Adaptive Broadband Mobile Ad-Hoc Radio Backbone System

DARPA NetCentric Demonstration – Ft. Benning, GA, January 2006 (invited paper)

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***Abstract* — This paper describes a novel autonomously adaptive networked radio system that provides a broadband tactical mobile backbone to enable netcentric warfare. The system was successfully demonstrated to seamlessly interconnect multiple heterogeneous networked radio systems during the DARPA NetCentric (NC) demonstration at Ft. Benning, GA in January 2006, serving as the high availability terrestrial backbone link between dismount units that were otherwise beyond communications range. Real-time tactical voice, video, and situation awareness (SA) data were reliably delivered over the network to support the planning and execution of a simulated tactical mission with all radio network operation conducted by active duty US military personnel. Each NC node operated as a vehicular or airborne relay mobile ad-hoc router for the terrestrial backbone tactical network. Routing in each ground vehicle selected between this terrestrial backbone path and an alternate satellite backbone for assured line-of-sight (LoS) and beyond line-of-sight (BLoS) communications.**

The broadband mobile ad-hoc radio system incorporates many innovative networking features to deliver breakthrough capabilities. Multiple discontiguous 1.2 MHz wide bandwidth segments are aggregated into a single RF waveform to ease frequency planning in crowded UHF spectrum bands. The system provides both high data rate and long range communications by autonomously adapting each link in the ad-hoc network topology to deliver the maximum possible throughput under dynamically changing link conditions. Prioritized delivery of time-sensitive and high value traffic is achieved through novel Quality of Service (QoS) mechanisms implemented in both the MAC and Network layers to ensure that the most important traffic is delivered during periods of network congestion. The reliable autonomous adaptation of the networked radio allows warfighters to focus on external events during tactical maneuvers without having to worry about communications connectivity.

Keywords-mobile ad-hoc network (MANET); Network Centric Communications; Tactical Communications; Heterogeneous Networking

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I. INTRODUCTION

With network-centric warfare, the focus shifts from the platform to the network [1]. Tactical radio networks consist of a collection of heterogeneous radio types distributed across an area of operations. Interconnection of these multiple radios requires a netcentric backbone for connectivity between forward deployed units and the tactical operations center (TOC). A combination of terrestrial and satellite backbone transport networks can be used to provide both high bandwidth and reliable connectivity. The DARPA NetCentric experiment in January 2006 demonstrated this capability to interconnect multiple distributed feeder networks with autonomous selection between terrestrial and satellite backbone paths.

The paper is organized as follows: Section II describes the Heterogeneous Networking Architecture demonstrated in the experiment. Section III describes the Terrestrial NetCentric Radio System, including architecture, waveform modes, and networking protocols. Performance during the exercise is covered in Section IV. Section V concludes the paper.

II. HETEROGENEOUS NETWORKING ARCHITECTURE

The DARPA NC Radio System provided the terrestrial backbone network for feeder stub networks integrated through a heterogeneous network gateway. Airborne relays with the primary mission to support communications were used to provide broadband connectivity over several tens of kilometers. Lower data rate SATCOM terminals were used to maintain BLoS connectivity during infrequent DARPA NC Radio System outages [2]. The vehicular autonomously selected the best available backbone network. Feeder stub networks (PRC-150, PRC-119, PRC-117, SECNET11, Soldier Radio, EPLRS, and MicroLite) were used for small unit tactical communications in the vicinity of the vehicular backbone node. All voice, video, and data traffic was transported between feeder networks over the backbone network. Command & Control (C2) information was managed by the Comand Post of the Future (CPoF) application. Figure 1 depicts the simplified network architecture where the vehicular node provided the autonomous backbone network selection between terrestrial and satellite paths.

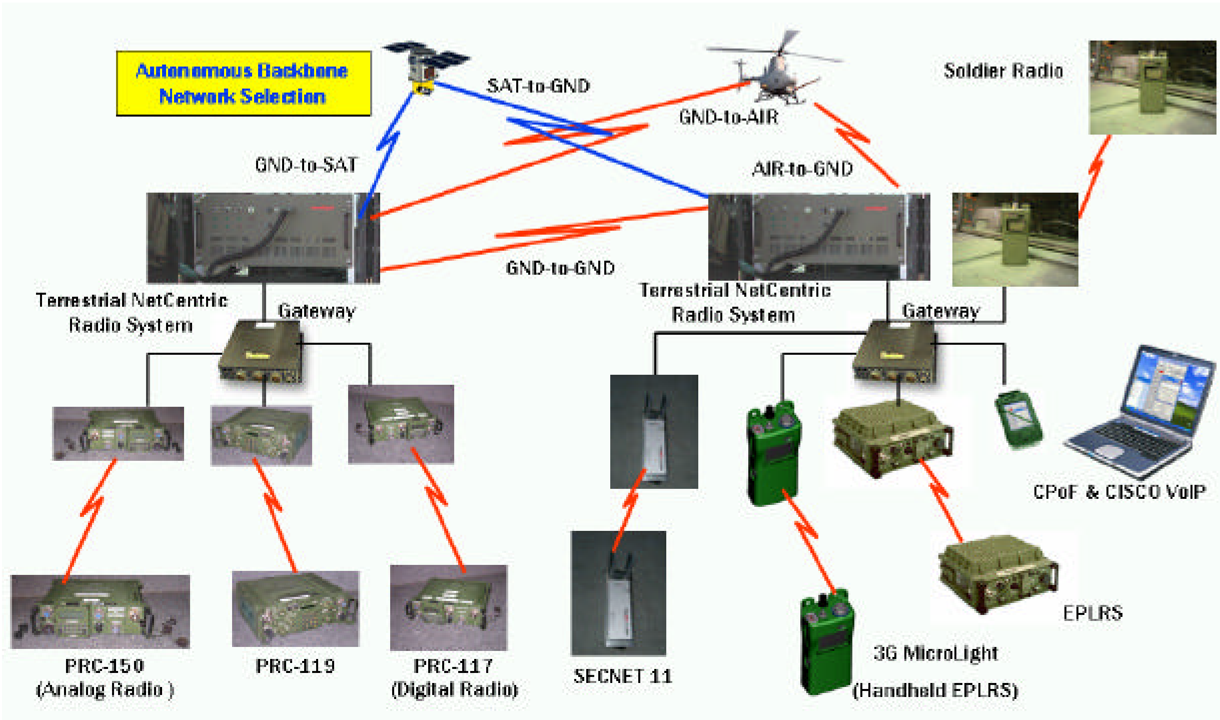

Figure 1. Simplified Network Architecture

III. TERRESTRIAL NETCENTRIC RADIO SYSTEM

A. NetCentric Radio Architecture

A high-level view of the architecture of each terrestrial NetCentric Radio node is shown in Figure 2. Antennas are connected to an RF distribution module that contains the necessary RF filters, switches, attenuators, and power and low-noise amplification for high dynamic range operation. An FPGA-based receiver/exciter module performs digital up/dn conversion and OFDM waveform modulation and demodulation with reference timing from the GPS/Rubidium timing sub-system. MAC and datalink neighbor discovery, QoS, and scheduling functions are implemented on a General Purpose Processor (GPP) running on a 'black' circuit card assembly (CCA). MANET routing functions run on a GPP on a 'red' CCA. An architectural placeholder is reserved for future insertion of embedded crypto. Full Red/Black security implementation was beyond the scope of this DARPA-led radio system development. The red CCA interconnects to user data and a data collection engine through an Ethernet hub.

Each node is GPS synchronized for uniform network timing. A Rubidium oscillator enables operation during GPS outages. An omni-directional antenna for horizon and low elevation coverage, and an overhead coverage antenna (or ground coverage for airborne radio deployments are power combined for hemispherical coverage. An external data collection system was used to log test data for radio network performance analysis.

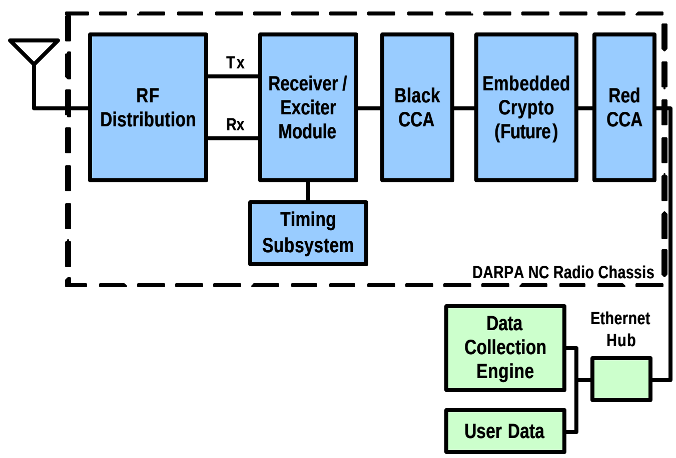

Figure 2. Terrestrial NetCentric Radio Block Diagram

B. Waveform Modes and Adaptive Data Rate (ADR)

The radio modem implements a half-duplex slotted TDMA frame structure with 5.8 ms slots. The waveform modes used a combination of different modulation, waveform coding and bandwidth settings to achieve the desired tradeoffs between data rate and receiver sensitivity. A node either transmits or receives on each time slot. When transmitting, one of seven possible OFDM-based waveform modes can be sent. The receiver modem autonomously discovers the transmitted waveform mode upon reception so that the transmitter may make waveform mode selections without closed-loop feedback. The waveform is capable of modulating from one to six non-overlapping 1.2 MHz wide frequency segments. Segments are placed within a 20 MHz bandwidth span and may be discontiguous to support fragmented spectrum allocations as shown in Figure 3. BPSK and QPSK modulation are supported with ½ rate Turbo FEC and an optional additional layer of Walsh Transform coding. From the many possible combinations of waveform formats, a subset of formats as shown in Table I was selected to incrementally step through increasing data rate modes as supported by link conditions. The most robust waveform mode (Walsh5-1) was used for neighbor discovery and maintenance.

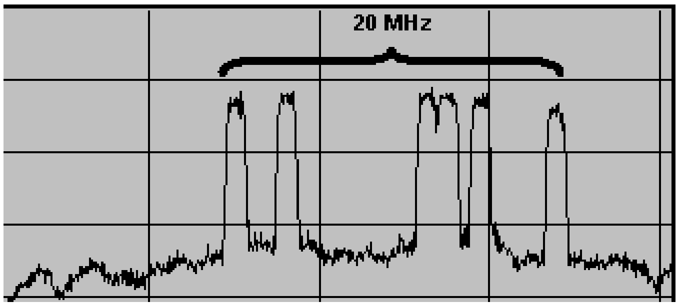

Figure 3. Discontiguous Spectrum Operation

TABLE I. WAVEFORM MODES

Waveform Mode	**Waveform Parameters**		
	Description	***Burst Rate***	***Sensitivity (dBm)***
Walsh5-1	BPSK, Walsh5, 1 segment	117 kbps	-105.8
Walsh5-2	BPSK, Walsh5, 2 segments	234 kbps	-102.8
BPSK-1	BPSK, ½ rate FEC, 1 segment	556 kbps	-99.5
BPSK-2	BPSK, ½ rate FEC, 2 segments	1.1 Mbps	-96.5
BPSK-4	BPSK, ½ rate FEC, 4 segments	2.2 Mbps	-93.5
QPSK-4	QPSK, ½ rate FEC, 4 segments	4.5 Mbps	-90.5
QPSK-6	QPSK, ½ rate FEC, 6 segments	6.7 Mbps	-88.7

The system utilized an Adaptive Data Rate (ADR) capability that automatically maintained the highest supportable data rates to all neighbor nodes. ADR independently adjusted the mode to every neighbor node in real time to maximize operating range and data throughput. The ADR algorithm accomplished this via closed loop mode control based on SNR at the receiving node and link packet error rates. Independent modes are maintained on each direction of every link.

C. Networking Protocols

This section describes the networking protocols implemented in the netcentric radio system. This includes MAC and networking protocols to support MANET operation in the terrestrial segment, QoS prioritization, unicast and multicast routing, and transit net for heterogeneous networking and autonomous backbone route selection.

The DARPA NC Radio System Networking protocols operate at layers 3 and below in the OSI model. The network layer enables unicast and multicast routing using Scoped Link State Routing (SLSR) and Receiver Oriented Multicast (ROM) respectively [3][4]. The Datalink layer includes a Neighbor Protocol (including Neighbor Discovery) and the Media Access Control (MAC) protocol. The MAC uses a Node Activated Multiple Access (NAMA) protocol to dynamically schedule time slot transmissions. NAMA is a topology dependent MAC protocol that uses the node identifiers, link data rate mode and bandwidth requests of the one- and two- hop neighbors as parameters in a pseudo-random function for channel access scheduling [5]. This approach effectively enables coordinated, collision-free, scheduling that is responsive to changing network demand with minimal overhead.

The DARPA NC protocol suite is Quality of Service (QoS) aware at the Network and Datalink layers to accommodate applications developed with QoS support in the standard TCP/IP protocol suite. Priority queuing is performed at both the Network and MAC layers. In the data link portion of the MAC, separate queues are maintained for each neighbor with a separate queue for each data rate and QoS level. Data is chosen for transmission in decreasing order from Highest QoS/Highest data rate to Lowest QoS/Lowest data rate.

To allow nodes to find their neighbors, and maintain knowledge of the two-hop topology of their neighborhood, periodic broadcast timeslots are allocated to a neighbor protocol. These timeslots, or control slots, are used by the neighbor protocol to send control packets to update neighbor information. No explicit acknowledgements of the transmissions are needed. Periodic transmissions of the neighbor data assure delivery of consistent information across the two-hop neighborhood.

The DARPA NC Radio system uses a Scoped Link State Routing (SLSR) algorithm for Unicast routing. SLSR introduces the concept of multi-level "scoping" to reduce routing update overhead in large networks. Each node stores the topology information in a topology table. Route updates are computed using the Dijkstra Shortest Path First algorithm [6]. The route on which the packet travels progressively approaches the true shortest path as the packet gets closer to its destination.

The networking software exports routes determined using SLSR into the IETF standard wired Internet routing protocols (e.g. RIP, OSPF, BGP) to support routing over multiple wireless and wired networks [7][8][9]. This allows the terrestrial backbone radio to provide a transit network capability.

The SLSR implementation has the capability of learning or its one-hop neighbors using a “hello” protocol between peer routing processes or directly from the data link portion of the MAC. By re-using the neighbor information from the data link, the SLSR control packet overhead is reduced since there is no need to re-send the inter-scope messages to the one-hop neighbors.

The DARPA NC Radios uses Receiver Oriented Multicast Routing (ROM) for multicast routing. It applies "on-demand" routing techniques to avoid channel overhead and increase scalability. It uses the concept of "Forwarding Group", a set of nodes which is responsible for forwarding multicast data, to build a forwarding tree for each multicast group. The forwarding group infrastructure reduces storage overhead and can handle a much looser connectivity among multicast members. The reduction of channel/storage overhead and the relaxed connectivity improve ROM scalability for large networks and stability for mobile wireless networks.

ROM is an example of a Forwarding Group Multicast Protocol (FGMP) that improves upon its predecessors by exploiting a receiver advertisement scheme which is more efficient than a sender-receiver advertisement scheme. ROM can coexist with any unicast routing protocol since it finds its own routes independently. ROM is required in full when used in conjunction with on-demand unicast routing protocols.

The netcentric radio contains a Network Layer routing function capable of both routing within the terrestrial backbone netcentric radio network and sharing the route information to a Commercial-off-the-Shelf (COTS) router for delivery of data to external destinations. This capability includes mechanisms employed to share unicast and multicast route information between the router embedded in the netcentric radio and a COTS router, such as a Cisco appliance. This function permits the netcentric radio router to support delivery of messages across the terrestrial backbone network when the sources and destinations are both inside and outside the terrestrial backbone, also called Transit Net.

Route information sharing with a COTS Router is accomplished using the Open Shortest Path First (OSPF) routing protocol. Both SLSR and OSPF are enabled on each netcentric radio router. Route redistribution techniques included both standard and non-standard techniques adapted specifically to meet the requirement to autonomously select between the terrestrial backbone netcentric radio network and the BLOS SATCOM network with preference for the terrestrial path. Route advertisement presented several challenges which were all overcome by adjusting OSPF parameters to prevent excessive route redistribution. None of the OSPF modifications implemented in this effort appear to have broken OSPF RFC compliance, as described in RFC 2328 [10]. The OSPF RFC does not describe redistribution methodology.

IV. NETCENTRIC RADIO PERFORMANCE DURING OPERATIONAL EXERCISE

The DARPA NC Experiment culminated in a live operational exercise on January 25th 2006. This exercise used all 14 DARPA NC network nodes (8 with DARPA NC Radios) participating in a 6 hour exercise at Ft Benning, GA. The nodes were deployed as Mechanized Infantry Battalion which was tasked with capturing two objectives at distances in excess of 75 kilometers from the forward command post. The exercise, dubbed "DNC-E Operation Long Haul", is summarized below and depicted in Figure 4.

1. All units assemble at Forward Operating Base McKenna (Battalion TOC, DARPA NC Node 1, located at McKenna – upper left corner – throughout exercise)
2. A Company (A Co HQ is DARPA NC Node 4) moves to Phase Line "Steel" and Cyclops 3 (UAV3, DARPA NC Node 8) deploys to provide Video Surveillance and Radio Relay.
3. B Company (B Co HQ is DARPA NC Node 3) moves to Phase Line "Steel". Deploy Cyclops 1 (UAV1, DARPA NC Node 5) and move Cyclops 3 (Node 8), to provide Radio Relay and Video Surveillance.
4. C Company (C Co HQ is DARPA NC Node 7) and Battalion TAC (Bn TAC is DARPA NC Node 2)move to Phase Line "Steel". Cyclops 1 (Node 5) and Cyclops 3 (Node 8) move as necessary for Radio Relay and Video Surveillance.
5. A Company (Node 4) moves to objective Montezuma and UAV's redeployed as necessary.
6. B Company (Node 3) moves to Objective Dawson, > 75 km from McKenna Base. UAVs re-deployed as necessary.
7. C Company (Node 7) moves to Americus and Battalion TAC moves to Preston.

The Operational Exercise was under the complete control of the Army and USMC Signal personnel. The operational team provided mission planning and directed all mission activities, including deployment of Communications Relays (surrogate UAVs).

The exercise spread the DARPA NC Radio Network over a roughly 100 km x 100 km operational box, with air-ground link distances of up to 62 kilometers. Throughout the exercise, including maximum range operation, all nodes maintained connectivity in the Network for the vast majority of the operation. Based on route availability data from the DARPA NC Radio Data Collection System, the Battalion TOC (Node 1) maintained complete network connectivity for over 99% of the exercise period. Operator reports of "virtually outage free" SA Displays and IP Chat further corroborate this high level of observed network availability. Figure 5 shows DARPA NC Radio connectivity in 30 minute increments during the exercise. Connectivity between nodes is displayed with green lines. The thickest lines, which comprise majority of those displayed, indicate a high data rate Mode 7 (QPSK-6) connection. Thinner, or dashed/dotted, green lines indicate connection at one of the lower data rates.

Neighbor discovery and maintenance is critical to maintaining traffic flow in a dynamically changing network. These features provide the link level connectivity that is used as the basis to determine network routing and assure that traffic is routed over the most advantageous paths/links. The operational exercise on January 25, 2006 demonstrated neighbor discovery and maintenance during worst-case highly mobile conditions. Figure 5 shows 9 time-sequenced frames of operation in a roughly 100 km by 100 km operational box. Links (represented by solid lines) were frequently changing both with respect to neighbors and data rate modes. The neighbor discovery and maintenance functions clearly worked as desired to maintain the network in this dynamic environment.

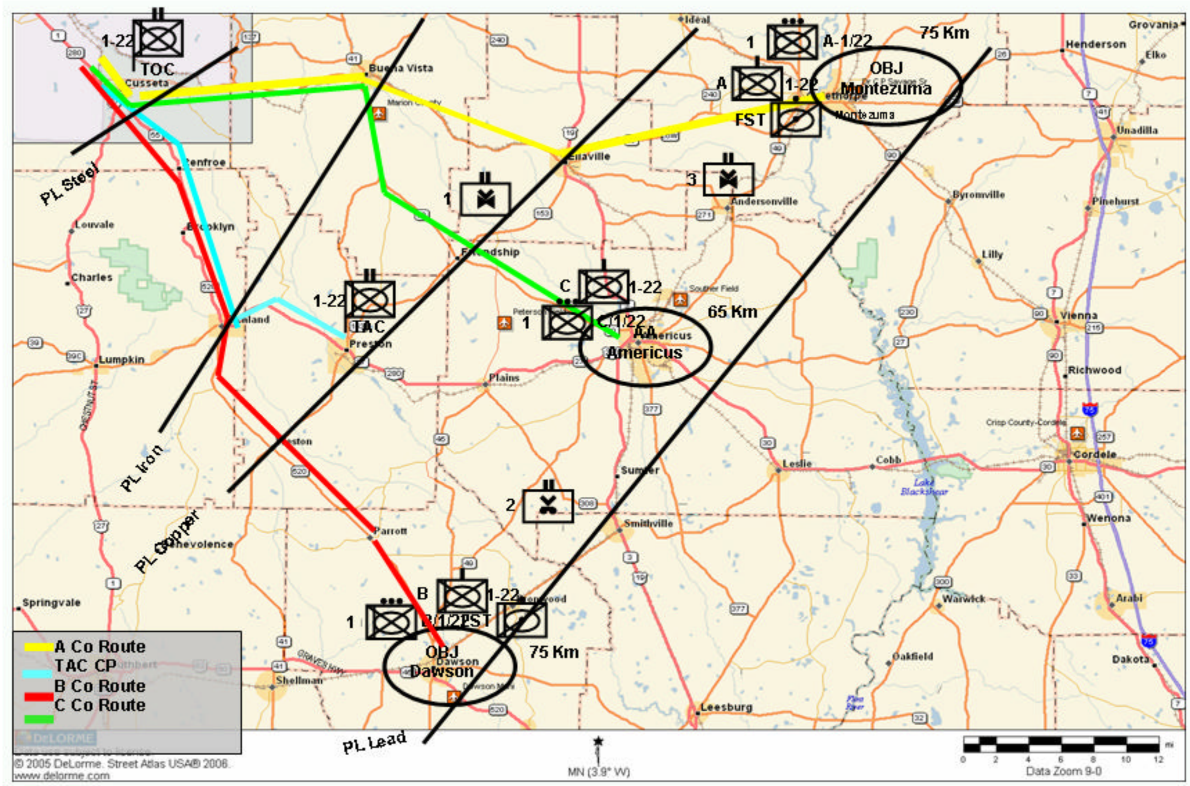

Figure 4. Operational Exercise Scenario

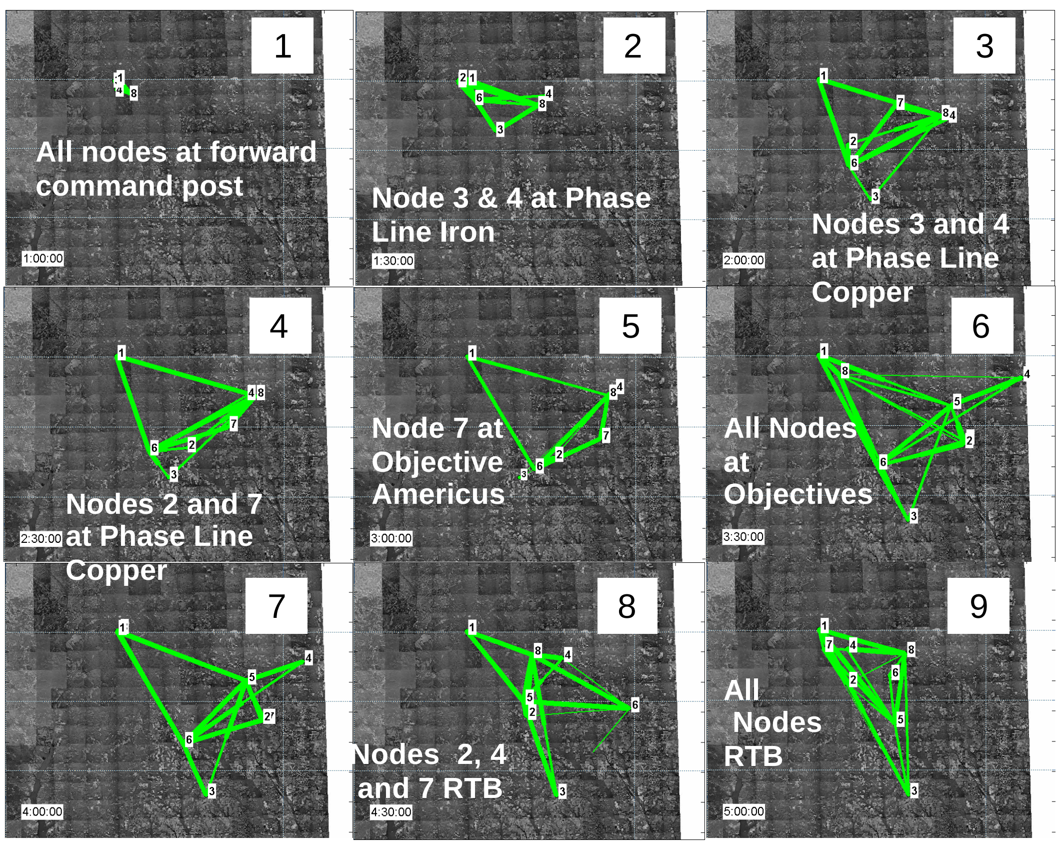

Figure 5. Topology Progression During Demonstration

The exercise included two 500 kbps video feeds: one from the Cyclops3 UAV (Fixed Wing Aircraft, Node 8) that was sent to the Battalion TOC (Node 1, at McKenna); and one that was sent from the Battalion TAC (Node 2) to the Battalion TOC. The Cyclops3 video feed was sent via a direct single hop air-to-ground link throughout the exercise. The Battalion TAC video was sent via a 2-hop ground-air-ground relayed link when the node was deployed. When the Battalion TAC was at or close to the McKenna assembly area the video was delivered directly to the Battalion TOC via a single hop ground-ground link.

Throughout the duration of the exercise the one-hop Cyclops3 video was received error free at the Battalion HQ approximately 91% of the time, based on recorded video packet delivery metrics. The 9% of operation with errors resulted in occasional degraded performance such as "tiling" and "smearing" although the video was rarely completely lost. The Battalion TAC video, which included mostly 2-hop relayed video, was received error free at the Battalion HQ approximately 75% of the exercise period. As expected, the Battalion TAC video showed more incidences of "tiling" and "freezing" due to the higher number of errors.

Figure 6 shows the nominal link ranges which were observed during development testing compared against the idealized maximum ranges. Actual ranges are reduced from ideal range by a number of factors including platform motion affects (pitch and roll of both airborne and ground platforms resulting in periods of reduced antenna gain), multipath effects, blockage and horizon effects (at longer ranges for air-ground links, blockage occurred primarily from trees) and RF variability of pre-production radios.

		Predicted Range (Ideal)[3]	Actual Range
Air-Air	QPSK-6	200 km	80 km
	BPSK-1	300 km	150 km
Air-Ground (9000 ft.)	QPSK-6	160 km	60 km
	BPSK-1	>250 km	150 km
Air-Ground (3000 ft.)	QPSK-6	80 km	27 km
	BPSK-1	160 km	68 km

[3]Ideal predicted range does not include RF variability, blockage, or horizon effects

Figure 6. Link Range Performance

The DARPA NC Radio Adaptive Data Rate (ADR) capability allowed seamless switching between the seven radio data rate modes as dictated by range and propagation conditions. This allowed the radio system to maintain network connectivity and data exchange even as pairs of nodes exceeded the usable link range for the higher data rate modes. Throughout the testing, ADR independently choose the highest reliable data rate mode for each link.

Figure 7 shows ADR operation on a two node air-to-ground link on a typical air-to-ground reconnaissance scenario test where the air node flew out to a distance of 120 kilometers. As the UAV node flew away, ADR automatically stepped down the data rate to maintain network connectivity and data exchange out to the maximum data range. At each step, delivered throughput compares favorably with modeled performance projections.

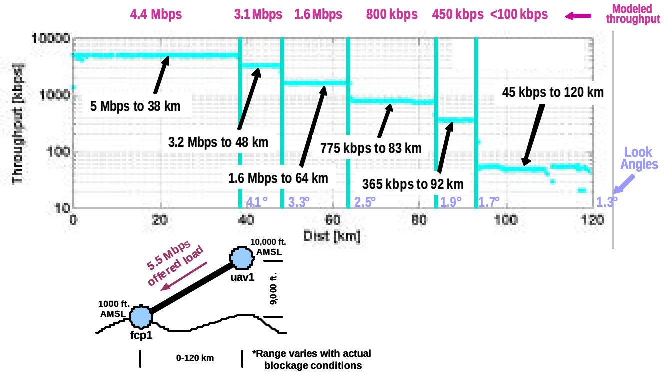

Figure 7. Adaptive Data Rate (ADR) Performance

Figure 8 shows packet delivery percentages for different QoS types as nodes maneuvered from a mesh topology to a relay topology with increasing separation and then returned to the original mesh topology. As the nodes moved away from one another, the ADR algorithm adjusted to maintain connectivity at a lower overall link and network capacity. Under these increasingly congested conditions (constant offered load with reduced network capacity), the results show that the higher QoS data was prioritized, resulting in higher delivery success percentages for EF than for AD and higher delivery success percentages for AD than BE for the duration of the test.

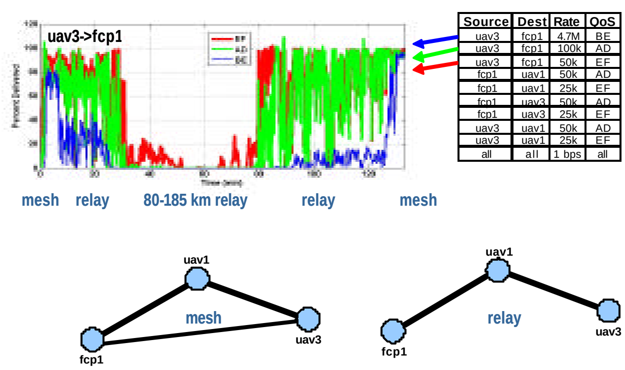

Figure 8. Topology Progression During Demonstration

Routed delivery of low data rate position/location information (PLI) packets during the operational test in excess of 99% network connectivity to Node 1 (Battalion TOC) under dynamic mobility conditions demonstrated reliable unicast routing over multiple hops in a mobile ad-hoc network.

The system was found to provide efficient and robust forwarding of multicast datagrams. Multicast routing trees were formed and maintained throughout the test and demonstration runs, while data was forwarding along the trees such that the number of transmissions required to disseminate the data was minimized while ensuring that all nodes able to receive the data (based on bandwidth and QoS constraints) did receive the data. As expected from design considerations, some duplication of multicast packets was observed due to network topology and data rate changes.

V. SUMMARY

The DARPA Net-Centric Radio Demonstration validated the Army's vision for NetCentric communications using mobile infrastructure for comms on the move. The Raytheon backbone radio network played a key role as a broadband interconnection between legacy radio systems. This capability achieved reliable data transfer under dynamically changing link conditions and node topologies while maintaining prioritized quality of service. Link ranges in excess of 60 km were demonstrated at the full 5 Mbps peak user data rate with connectivity maintained to distances over 120 km using airborne relays performing a "comms-primary" mission.

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